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Ca depletion and the presence of dust in large scale nebulosities in radiogalaxies (I)

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Abstract. We show that the study of the Calcium depletion is a valid and highly sensitive method for investigating the chemical and physical history of the very extended ionized nebulae seen around radio galaxies (EELR), massive ellipticals and 'cooling flow' galaxies. By observing the near IR spectrum of nebular regions characterized by low excitation emission lines (LINER-like), we can use the intensity of the [CaII]$\lambda\lambda 7291, 7324$Å doublet –relative to other lines, like Hα– to infer the amount of Calcium depletion onto dust grains. The presence of dust in these objects –which does not necessarily result in a measurable level of extinction– would favour a 'galactic debris' rather than a 'cooling flow' origin for the emitting gas. Before aplying such test to our data, we study four possible alternative mechanisms to dust depletion and which could have explained the absence of the [CaII] lines: a) ionization of Ca^+ from its metastable level, b) thermal ionization of Ca^+, c) a high ionization parameter and/or a harder ionizing contiuum than usually asummed and d) matter bounded models associated to a hard ionizing continuum. We show that none of these alternative mechanisms explain the absence of the [CaII] lines, except possibly for the highly ionized EELR where a high ionization parameter is required combined with a soft power law. We thus conclude that for the other low excitation emission regions (cooling flows, liners, low excitation EELR), the abscence of the CaII lines *must* be due to the depletion of Calcium onto dust grains.

Key words: atomic processes – ISM: dust – Galaxies: cooling flows, radiogalaxies

1. Introduction

The study of the interstellar medium (ISM) of external galaxies provides important information about the global kinematic (inflow, outflow) of such gas, its chemical composition and the implied star formation history, its mass distribution, etc. This gas forms a vital part of the record of the formation of the parent galaxy, and the evolutionary processes involved.

How can this material be studied in details? One way is to have it illuminated or excited by a powerfull AGN, giving rise to the phenomenon of extended emission line region (hereafter EELR). The drawback of course is that it only allows us to look at a restricted class of galaxy. The large scale EELR phenomenon is observed in a majority of the most powerful radiogalaxies with EELR extending to radial distances of up to 100 kpc from the nuclei (Tadhunter 1986; Baum et al. 1988), much larger radii than the stellar population distribution of the parent galaxy. The morphologies and kinematics of such regions cover the full range from regular disc/ring systems to chaotic systems for which no pattern can be discerned. Their spectrum show strong emission lines, covering a wide range in ionization. It is generally accepted that the EELR are ionized by some mechanism connected with the nuclear activity, but there is no full concensus on the excitation mechanism. Some objects show evidences for an interaction between the radio jets, which transport energy to the outer radio lobes, and the gas in the outer region. Maybe this interaction is responsible of the excitation of the gas through some kind of shocks (Sutherland, Bicknell & Dopita 1993). For other objects, that

do not show evident spatial coincidence between the radio structures and the EELR, the excitation might be due to direct photoionization by the nuclear ionizing radiation field (Robinson et al. 1987: hereafter RBFT87). A reduced scale version of the EELR is the one observed in many Seyfert galaxies (Haniff, Ward & Wilson 1988) where the ionized gas may extend up to a few kpc although it is brightest within the central 100–300pc. The EELR morphology tends to be conical (Wilson & Tsvetanov 1994). Its detailed observation is complicated by presence of the very luminous stellar background of the bulge. In normal bright ellipticals, quite weak extended nebulosities of low excitation is a common phenomenon (Buson et al 1994, Goodfroij 1994). The very large scale gas around radio-galaxies and on which we focus here presents the advantage that the lines are observed against the sky background rather than against the bright parent galaxy bulge.

The origin of the gas making up these *large scale* extended nebulosities remains unknown. Furthermore, the distinction between these and the filamentary nebulae seen in some clusters and around some massive ellipticals and often identified with cooling flows, is unclear. We do know, however, that this gas in every case is chemically enriched as compared to primordial gas. Emission line analyses (RBFT87) show common element abundances to be within a factor of a few ($\leq$) of Solar and also to be rather uniform over all the objects observed.

The two most likely explanations for the origin of the material are:

a) debris from recent tidal interactions and mergers

b) gas cooling from the hot ($\sim$ virial) phase which from X-ray observations (Forman, Jones & Tucker 1985) has been shown to exist around massive ellipticals and inside galaxy clusters

The main arguments behind these explanations are the following:

a) Heckman et al. (1986) showed that a large fraction of powerful radiogalaxies have morphological features – shells, tails, loops, etc– similar to those produced in numerical simulations of galaxy interactions (e.g., Toomre and Toomre 1972, Quinn 1984). This could indicate that the activity has been triggered either because fresh gas has been accreted from outside or because prexisting gas in the galaxy has been caused to collapse to the core as a result of the interaction. This interaction scenario is also supported by observations of a few nearby radio galaxies which, apart from morphological peculiarities, show large misalignments between the stellar and the gaseous rotation axes, indicative of an external origin for the gas.

b) Hot X-ray coronae ($T \geq 10^4$K) are a common feature of bright early-type galaxies. Within some critical radius, radiative cooling becomes important, leading to the development of the so-called 'cooling flow' hypothesis (Nulsen, Stewart & Fabian 1984,Thomas 1986, Thomas et al. 1986) Eventually, condensations or filaments could be formed, dense and cool enough to radiate detectable optical emission lines. Most powerful radio galaxies are too distant for the characteristic X-ray emission to be currently detectable, but it is quite plausible that the EELR gas has condensed out of a surrounding cooling flow. Any discovery of their EELR as consisting of extensive optical filaments would argue in favour of the cooling flow hypothesis.

Distinguishing between these alternative hypotheses has been attempted using gas kinematic measurements (Tadhunter, Fosbury & Quinn 1989) which show that the radio galaxy EELR generally have a high specific angular momentum which is difficult to reconcile with the cooling flow picture. An alternative approach is to look for the presence of dust associated with the EELR gas. If the gas has cooled directly from a hot phase, there will have been no opportunity for dust to form, according to the standard cooling flow theory. Any dust introduced from galaxies into the hot intracluster medium will be rapidly destroyed (Draine & Salpeter 1979). We would need a mechanism to produce this dust once the gas has cooled down (Fabian, Johnstone and Daines 1994). If, on the other hand, the material has fallen in during a merger, the dust/gas ratio is expected to have a value appropriate to the gas chemical composition found in normal galaxies.

Determining the presence or absence of dust is important because:

-of its relevance in deriving chemical composition which takes into account the effects of depletion of metals unto dust grains

-of the implication for the star formation history and the ISM evolution: when does dust form? (and so stars?)

-of the effects of dust on the apparent morphology of continuum and line features: pure absorption (reddening) and/or scattering (blueing/polarization)

We discuss below how the absence of the forbidden [CaII] lines can be used to infer the presence of dust mixed in with the emission gas. We assess in detail all the most plausible *alternative* explanations to that of internal dust for explaining the absence of [CaII] lines. As no acceptable alternative solution is found, we conclude in favour of the validity of the method initially proposed by Ferland (1992). We however adapt and optimize the [CaII] dust detection technique to the context of the EELR studies in which we are involved. The observational results and their interpretation will be presented in a subsequent paper.

2. Outline of the method

To investigate how the forbidden Calcium doublet of [CaII] in the infrared is affected by the physical condition encountered in photoionized plasma, we outline first the computer code which we used and then proceed to illustrate how the [CaII] lines might be used to infer dust in the ISM of galaxies and thus our interest in securing these conclusions by closing up the possibility of alternative interpretations.

2.1. The photoionization code MAPPINGS.

To compute the emission lines used in our study, we have used the multipurpose photoionization–shock code MAPPINGS (c.f., Binette, Dopita & Tuothy 1985). The Ca^+ ion is considered as a five level atom. Its structure is shown in Fig. 1.

One interesting aspect of the updated (Binette et al 1993a,b) code MAPPINGS is that the effect of dust scattering on the line transfer is explicitly solved using the numerical solution of Bruzual, Magris & Calvet (1988) as described in Appendix A of Binette et al 1993b. Other effects of dust on the ionization structure as well as on the thermal balance of the plasma are considered followoing the prescriptions of Baldwin et al. (1991 see Appendix C). The dust grain charge is calculated self-consistently and the formula describing the photoelectron energy distribution and the yield are from Draine (1978) but with a cap of 0.2 for the yield at high photon energies.

We now proceed to define the parameters employed in the calculations. Most of these are derived from our observational knowledge of EELR although we recognize that it is incomplete and can be biased by particular diagnostic tools which are employed.

2.1.1. Metallicity

For definiteness, we adopt a set of solar abundances (Anders & Grevesse 1989) for the trace elements, in line with the finding of RBFT87 who indicated values for the EELR not radically different from solar. The solar abundance of (*not* depleted) atomic Calcium is 2.2×10^{-6} by number relative to hydrogen. Depletion into interstellar dust grains is known to reduce this abundance in the local ISM by a factor of ~ 5000 (Whittet 1992) so that if depletion was taking place in the partially ionized EELR plasma, even a small dust-to-gas ratio might be sufficient to eliminate any detectable trace of atomic Calcium.

2.1.2. Geometry

It's been accepted for a long time that the NLR and the EELR are formed by individual clouds that are ionized by the central source. In most models presented here, each emitting cloud is considered as a radiation bounded slab (optically thick to the Lyman continuum) which comprises: (1) a fully ionized region, closer to the illuminated face and responsible for the high ionization lines; (2) a partially ionized zone (PIZ), where the low ionization lines like CaII are emitted. The boundary of the photoexcited regions (1 + 2) is defined as the depth where the following two conditions are simultaneously satisfied: a) The unabsorbed ionizing flux is < 1 % of the impinging flux and b) the ionized fraction $n_{H^+}/n_H \leq 1$ %. Matter bounded clouds will be considered in Sect. 3.4. As we want to concentrate on the depletion phenomena, we will simplify the calculations by not considering any neutral region (3, see Fig. 2) beyond the PIZ which would contain dust, the effect of which would be to cause additional extinction for an hypothetical and unfavorably placed observer looking from the back of the slab. We have verified that the results reached here using line ratios of similar wavelengths are not altered by the presence or not of this neutral absorbing zone.

2.1.3. Gas density

We adopt a representative density for the EELR clouds of 300 cm^{-3}. Typical electron densities values measured vary between a few tens (or less) to a few hundreds. The densities derived from forbidden line ratios might not apply to every subregion, but they are sufficietly low to consider the low density limit as a generally valid and very good approximation to the physical conditions affecting the CaII lines of large scale EELR. In the low density regime, the effects of density variations on the emission line ratios which are considered in this paper are very small by comparison to the effects of other parameters like the ionization parameter or the hardness of the ionizing continuum.

The calculations consider the gas pressure to be constant within the cloud (isobaric models) with the density behaviour modulated with depth into the cloud by the behaviour of the temperature and by the ionization fraction of the gas.

2.1.4. The ionizing continuum and the ionization parameter U

We implicitely assume that the dominant ionization mechanism of the ionized gas in radio galaxies is photoionization. It has been shown by RBFT87 that a hard continuum extending well down into the soft X-ray region, despite some discrepancies with the observed spectra, can be considered to reproduce generally well the measured line ratios. This continuum can take its source in the active nucleus or be locally generated (e.g., fast shocks: Binette, Dopita, Tuohy 1985). We have considered power law (PL) distributions of various values of α ($F_\nu \propto \nu^{+\alpha}$) as well as hot blackbodies (BB) of temperature $T_{bb} \approx 10^5 K$ in order to study the effects that hardness has on our conclusions.

The ionization parameter, a measure of the excitation level of the ionized gas, is defined as the quotient between the density of impinging ionizing photons and the density of the gas cloud:

$$U = \frac{Ionizing\, energy\, flux}{c\, n_H} = \frac{\int L_\nu d\nu / h\nu}{4\pi r^2 c n_H}$$

where L_ν is the monochromatic luminosity of the source, r the distance of the cloud to the continuum source, n_H the density of the gas and c the speed of the light.

We find that the parameters having the strongest effect on the line spectrum are the ionization parameter U and the mean ionizing photon energy (*i.e.,* hardness of the continuum).

2.2. How to detect dust

How can we detect dust within the gas associated with EELR? We here summarize different techniques and compare their sensitivities.

a) Reddenning: given the nature of the gas distribution and the fact that it is ionized externally (unlike HII regions which are internally excited), the extinction may not be necessarily sufficient high to be easily detected using optical observations. Indeed, the EELR ratios studied by RBFT87 show little or no reddening. Furthermore a small enhancement of the Balmer decrement over recombination case B might be interpreted as resulting from collisional excitation rather than from reddening.

b) Scattering: polarization measurements of high redshift radio galaxies (di Serego Alighieri *et al.* 1989, 1992, Januzi & Elston 1991, Tadhunter *et al.* 1992) show conclusive evidence for scattered nuclear light over large volumes and, altough there are reasons to believe that the scattering medium is dust, it is difficult to rule out entirely Thomson scattering by hot electrons. Detailed studies of the low redshift galaxy PKS2152-69 do, however, show polarized continuum radiation from highly excited extranuclear gas cloud with an energy distribution which is so blue that it must arise from dust scattering (Fosbury *et al.* 1990).

c) Infra-red thermal dust emission: the IRAS satellite has shown that many galaxies radiate significant fractions of their energy in the far infrared sprectral region. Significant masses of dust at temperatures of around 40K are responsible of this radiation at wavelengths of 60μm and beyond. In many cases the FIR spectral energy distributions is still rising at 100μm, out of the spectral range detectable by IRAS. The cool dust can only be detected at milimetre and submilimetre wavelengths. A strong limitation of this technique is the very poor spatial resolution of the IRAS satellite. Groundbased studies of the far IR emission of galaxies in the sub-mm range also exist(*e.g.* Clements, Andreani & Chase 1993), but still with poor spatial resolution. Although it is possible to infer masses and temperatures of the warm and cool dust components (dependent on models), the spatial distribution of the dust is not known.

d) Indirect effects on the line spectrum. There are several ways this can happen: effects of dust on the gas temperature (photoionization of dust grains may raise the temperature of the plasma), effects of dust on the ionisation structure (dust grains selectively absorb ionising photons of lower energies), and influence on apparent chemical composition via the depletion of refractory elements onto dust grains. The first effect does not provide a unique interpretation for the unusually high temperatures seen in some EELR (Tadhunter, Robinson & Morganti 1989) while the second effect cannot be discriminated against reliably since even dust-free photoionization models are still too uncertain to be used as absolute reference point. For these reasons, the last effect is the only clearly promising one and is looked into details below.

Calcium is very sensitive to the presence of dust as it is always found to be depleted in the interstellar medium (e.g., Crinklaw, Federman & Joseph 1994). Photoionization calculations appropriate to LINERS –a hard ionizing spectrum with a relatively low ionization parameter– invariably predict the [CaII]$\lambda\lambda$7291, 7324Å doublet ($4s^2$S-$3d^2$D) to be very strong (Ferland 1993). These two forbidden lines (hereafter F1≡ λ7291Å F2≡ λ7324Å) have a high critical density $\sim 10^6$ cm^{-3}. The latter line, 7324Å is the weakest of the doublet and is furthermore blended with the [OII]λ7325Å multiplet. The other line, λ7291Å lies some 30Å shortward of [OII] and is therefore straighforward to isolate given reasonable spectral resolution. The fact that any of these doublet lines are generally not seen in LINERS but are so in some novae when their envelopes have reached the appropiate ionization level can be interpreted as evidence of Calcium depletion onto dust grains in the former objects. Since EELR which are the subject of our investigation are often seen

in the ionization parameter region of the line ratio diagnostic diagrams occupied by LINERS ($10^{-4} \leq U \leq 10^{-3}$), we can similarly use the [CaII] doublet measurements to infer whether or not there is depletion taking place in EELRs and thus conclude whether dust is also mixed with the gas as is thought to be the case in LINERs.

The above arguments have already been used for several objects with 'cooling flow' filaments by Donahue & Voit (1993) to infer the presence of dust mixed with the ionized gas. Ferland (1993) has shown the great sensitivity of this method to the presence of dust under NLR conditions. We now show it to be also the case under EELR conditions. We present two diagnostic diagrams in Fig. 3, the ratio [CaII]/Hα (7291/6563) and the ratio [CaII]/[ArIII] (7291/7135) as a function of the ionization parameter U. The variable parameter distinguishing the three different sequences in U is μ, the dust-to-gas ratio of the plasma expressed in units of the solar neighborhood dust-to-gas ratio. The dramatic difference in line ratios between the grain depleted Ca/H ($\mu > 0$) and the undepleted case ($\mu = 0$), shows the sensitivity of this method, particularly for low values of U.

3. Possible alternative explanations to depletion.

Before we carry the conclusions of the current analysis to the interpretation of our observations (Villar-Martín & Binette 1995), we report first on our effort in investigating other possible alternative mechanisms to dust depletion. If the warm Ca^+ region predicted by standard models does exist, then Calcium depletion becomes the only reasonable explanation for the non detection of the doublet lines. What we consider in this section is the possible NON EXISTENCE of the emitting [CaII] region by investigating different mechanisms which could eliminate it. During our investigation, we require however that successfull models do not result in important discrepancies with other observed line ratios. The mechanisms we have considered to eliminate the [CaII] region are

- Ionization of Ca^{+*} by Lyα and soft continuum photons from the metastable level of Ca^+
- Thermal (collisional) ionization of Ca^+
- Photoionization with a much harder continuum or a much higher U than usually asummed

3.1. Ionization by Lyα and soft continuum photons.

Wyse (1941) proposed that the ionization of CaII from the metastable level by Lyα photons, could explain the fact that the IR lines of CaII at 8498, 8542 and 8662Å appear in emission near the maximum phase of Me variables, whereas the H and K lines only occur in absorption. Trapped Lyα photons could also play a part in ionizing metastable Ca^{+*} as suggested by Wallerstein et al. (1986).

We investigate here if this process is important under the conditions found in EELR clouds. In order to do this, we add two terms to the ionization equilibrium equation of CaII. One which considers photoionization of excited Ca^{+*} by the impinging UV continuum. The other is photoionization of excited Ca^{+*} by the nebular Lyα photons. The statistical equilibrium equations give the relative population of the mestastable level, which turns out to be, under EELR conditions, $\frac{n_{3d}}{n_{4s}} \sim 10^{-7}$, being n_{4s} the density of Ca^+ ions in the ground level. With such a negligible population, the density of ionizing photons must be very high to increase the ionization rate to a non negligible level as compared to the ground state ionization rate. A simple estimate presented in Appendix demonstrates this level to be out of reach.

In summary, the very diluted radiation fields and the low densities appropriate to the EELR implies an extremely small population for the excited levels which prevents the ionization of Ca^{+*} by Lyα and soft continuum photons from being of any significance.

3.2. Thermal ionization of Ca⁺.

We investigate here the possibility of collisional ionization by thermal electrons of Ca^+ to Ca^{++}, a process which is important when the electronic temperature becomes higher than 20000K (Jordan 1969). In order to establish a comparison in U, we have considered two extreme cases in our calculations, log$U = -4$ & -2. To illustrate how a much harder continuum will result in much higher gas temperatures, we also use two different PL of index $\alpha - 1.4$ and -0.4. Note that such a hard continuum as $\alpha = -0.4$ is probably quite unrealistic. However, our intention here is simply to test whether very high temperatures can be achieved with photoionization models and specifically near the Ca^+ region. The results are shown in Fig. 4 as a function of depth in the photoionized slab. Of the eight plots, the four upper ones correspond to $\alpha = -1.4$ while the four at the bottom to $\alpha = -0.4$. The four plots on the right, have logU$= -2$, and the four on the left, logU$= -4$. Two plots therefore are shown for each pair of [U, α] values: one is the the temperature T4 in units of 10000K and the one immediately underneath is the intensity of F1 ($erg.s^{-1}.cm^{-2}$), both as a function of the depth in units of $10^{20}cm$ into the slab. These plots allow us to see the correspondig electron temperature to the position where the bulk of the [CaII]F1 emission takes place.

For the traditional PL of index $\alpha = -1.4$, the electron temperatures are not anywhere near high enough for the process of thermal ionization to be relevant. Harder continua and increasing U values do produce higher temperatures, but, unless U are unrealistically high (even logU= -2 is not enough), the gas is never hot enough. Thus, realistic photoionization models are *not* able to heat the gas sufficiently to thermally ionize Ca^+. We might conjecture that there could be an additional heating source like shocks which could raise the temperature of the gas. This would be an interesting point for further investigation.

3.3. Effects on F1 of varying U and the continuum hardness.

We now investigate how the F1 line might become undetectable by simply varying arbitrarily the ionization parameter or the continuum hardness. Fig. 5 shows six diagnostic diagrams with the absciss always representing the line ratio [OI]λ6300/[OIII]λ5007. The [OI]/[OIII] ratio monotonically increases with decreasing gas excitation (i.e., with decreasing U) and is therefore a good measure of the excitation level of the gas. Each diagram shows in ordinate a different line ratio which can be related to a given gas property. [OI]λ6300/Hα, for instance, might measure the hardness of the continuum. In the last diagram, the ordinate corresponds to the quotient F1/[OI]λ6300. The three sequences of models shown in each diagram differ by the slope of the power law which takes on the values of $\alpha = -1.4, -1$ and -0.4. The values of Log U covered by each curve is in the range -4 to -1. Our aim is to look for models which can decrease the F1 intensity below the detection limit. Let's look at how we might define a practical detection limit. The open squares in the diagrams of Fig. 5 represent line ratios measured by RBFT87 in several EELR. The faintest line they measure is typically HeIIλ4686. The mean ratio of HeIIλ4686/[OI]λ6300 observed is $10^{-0.4} = 0.4$ for the large scale nebulosities. We establish our 'artificial' detection limit in the following way: since HeII is one of the weakest line successfully measured by RBFT87, we will assume that any line fainter than 0.4 below the [OI]λ6300 flux is not detectable. In the last diagram, the region where F1 falls below this detection limit is shown by a dash line grid. Any model found in this area is deemed successful in explaining the non-detection of F1 without requiring depletion.

We see that for the standard PL ($\alpha = -1.4$), only models with high U (log U> -2) decrease log(F1/[OI]) below –0.4. These models, as we can see in the diagrams, would therefore be valid only for the high excitation EELR, but not for LINERs, cooling flow filaments, or EELR of low and intermediate excitation. On the other hand, increasing the hardness of the continuum (flatter power laws), helps F1 to get fainter with respect to [OI]λ6300, but the discrepancies with observed line ratios in other diagrams become totally unacceptable (see top two diagrams of Fig. 5).

It is interesting to compare a BB sequence (1.2×10^5K) with the canonical PL sequence $\alpha = -1.4$. We see that both ionizing continua reproduce rather well the observed line ratios as was earlier shown by RBFT87. From these line ratios alone, there are no reasons to favour power laws over hot blackbodies. A similar conclusion was reached by Binette, Robinson and Courvoisier (1988) for the mean NLR spectrum of Seyferts.

A BB produces a much stronger F1 compared to [OI]λ6300 than any of the power laws considered. One reason for this is that the fraction O^o/O^+ in the PIZ is completely controlled by the charge exchange reactions of O^o and O^+ with H^+ and H^0, respectively, and not by direct photoionization of O^o. This is not so for Ca^+/Ca^o which is free to respond to the different amount of hard photons (the only one to make it to the PIZ) available in a PL or a BB. We conclude from the last diagnostic diagram that the BB models could not explain the abscence of F1 from the observed spectra without invoking depletion.

3.4. Effects on F1 of truncating clouds

We showed in the previous section that a harder continuum can potentially bring F1 under the detection limit but result in important discrepancies with the low excitation lines. The reason is that the partially ionized zone (PIZ) where most of the low excitation lines are generated gets larger and larger with increasing hardness of the continuum. If the clouds were truncated, the smaller PIZ would generate weaker low ionization lines, thus improving the overall fit.

We have investigated models with $\alpha = -0.4$ which were truncated at a depth which satisfies a given criterion based on a specific line ratio. This has been done in two ways:

1) The criterion in this case is to truncate the calculations when OIII/Hβ has reached a value of 10 which is the typical ratio for the high excitation EELR.

The sequence of models shown in Fig. 6 are separated by a factor of 0.14dex in U. Altough there are still discrepancies, there is a notable improvement compared to the radiation bounded models of Fig. 5. The predicted line ratios are now located closer to the observed data (same scale as in Fig. 5). We conclude that models with a hard ionizing continuum must be matter bounded in order to fit acceptably most observed ratios.

What happens now with F1/[OI]? In the last diagram of Fig 6, we see that all these models produce F1 above the detection limits and cannot therefore explain the non detection of Calcium.

2) The second method consists in imposing that the models produce F1 under the chosen detection limit (F1/[OI]=0.4) and check if such models agree with the position of the observed line ratios in the rest of the diagrams.

The models in the sequence which satisfy this criterion are found in the range $3.7\times10^{-3} \leq U \leq 2.7\times10^{-2}$. They are represented in Fig. 6 as open triangles connected by a solid line. As we see in the top left diagram, the ratio [OIII]/Hβ is not any more defining a simple trend with excitation (which is represented by the ratio [OI]/[OIII]). Furthermore [OI]/Hα remains a discrepant ratio as in Fig. 5. So although it is in principle possible to satisfy the F1/[OI]=0.4 criterion with a hard power law, the truncation must be done at a specific yet *ad hoc* depth and furthermore the previous trend of excitation with U has disappeared.

Without rejecting the possibility of a more complicate mixture of matter and radiation bounded models, we believe that simply truncating clouds does not convincingly solve the problem of the weakness of the CaII doublet and dust depletion remains the most likely interpretation.

It is interesting to note that truncated clouds adjust better the HeII/Hβ ratio (bottom left diagram) as proposed before by Morganti *et al.* (1991) and Viegas and Prieto (1992).

4. Conclusions

This work is based on the method proposed by Ferland (1993) to investigate the presence of dust mixed with the gas of the Narrow Line Region of active galaxies. Because photoionization models predict remarkably strong forbidden lines [CaII]$\lambda\lambda7291, 7324$Å assuming reasonable abundances of atomic Ca, the basic idea is to infer a systematic depletion of Calcium onto dust grains whenever the infrared [CaII] lines are observed very weak or undetected. This test of the dust content was applied to cooling flow filaments by Donahue & Voit (1993) who concluded on the presence of dust.

We have shown here that this sensitive method is also applicable to the conditions found in the EELR of radiogalaxies. In order to make more secure any inference about the presence of dust based on [CaII] lines, we have investigated alternative explanations for their absence: ionization of Ca^{+*} to Ca^{++} by Lyα photons and soft continuum photons from the metastable level of Ca^{+}, thermal ionization of Ca^{+}, ionization of Ca^{+} due to either a very high U value (ionization bounded case) or to a hard continuum (with truncated clouds). Except for the highly excited EELR which might not possess any Ca^{+} region due to their high ionization level, the results are negative: none of the alternative mechanisms or models studied can explain the absence of the [CaII] lines without dust depletion.

Our conclusion is that the dust content test appears generally valid for the EELR of radiogalaxies (unless the excitation level of the gas is extremely high). This will allow us to make important conclusions about the origin of such gas, discriminating between galactic debris and the standard cooling flow theory.

A BB ionizing continuum characterized by a temperature of 1.2×10^5K can reproduce the observed line ratios of the EELR at least as well as a PL of index $\alpha = -1.4$. On the other hand, the F1/[OI] from a BB is higher than that of a PL so the case in favour of depletion is even stronger.

In a follow up paper, we will present long slit spectra of EELR, cooling flow filaments and Seyfert 2 NLR, all taken in the region of the [CaII] doublet. The goal will be to apply the test of the Calcium depletion described above in order to conclude whether or not the gas in these nebulosities is mixed with dust. This will be our starting point for deciphering the origin of the emitting gas.

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A. Appendix

By comparing the estimated photoionization rates from the excited level 3d of Ca^{+*}, Π_{3d}, to that from the ground state 4s of Ca^{+}, Π_{4s}, we show that photoionization of excited Ca^{+*} is a negligible process.

A fundamental parameter which determines the importance of the ionization rate from the metastable level is its relative population with respect the ground state: $\frac{n_{3d}}{n_{4s}}$, being n_{4s} the density of Ca^{+} ions in the ground level and

n_{3d} the density of Ca$^+$ ions in the metastable level, 3d. To evaluate this fraction, we have solved analytically the statistical equilibrium equations. To simplify the calculations we have considered a three level atom, reducing the two 4p sublevels (see Fig. 1) to a single level and the same for the 3p sublevels. We have taken into account all the processes (collisional and radiative) which can populate or depopulate each of the levels.

The resolution of the system of three equations gives us the ratios $\frac{n_L}{n_{Ca^+}}$, with L=3d,4s,4p, being n_{Ca^+} the total density of Ca$^+$ ions. The density and temperature we considered were $300cm^{-3}$ and 10000K, respectively. From this we deduced the relative population with respect the ground state. The results turn out to be:

$$\frac{n_{3d}}{n_{4s}} \sim 10^{-7}$$

and

$$\frac{n_{4p}}{n_{4s}} \sim 0$$

The negligible population of the upper 4p level prevents any contribution by cascade to the population of the 3d level, therefore collisional excitation is the only important mechanism populating the metastable 3d level. This is consistent with the fact that we do not observe the triplet of Ca$^+$ (8498,8542,8662) (4p to 4s) in any EELR although it is observed in the broad line region of AGN where densities are higher by many order of magnitudes.

a) Ionization of Ca^{+*} by soft continuum photons.

The soft UV counterpart of the ionizing continuum provides a source of ionization for both Ca$^+$ (IP: 11.9eV) and Ca^{+*} (IP: 10.2eV). To estimate the photoionization rates, we will make the following approximaptions:
1) At the fairly large depth in the cloud where the specie Ca$^+$ becomes abundant, we only need to consider photons with energies $< 13.6eV$, the ionization potential (IP) of H^0, because photons just above this energy have already been absorbed and also because of the rapid decrease of the photoionization cross section with increasing energies.
2) The ionizing continuum which reaches the PIZ is considered to be the soft UV counterpart of an ionizing PL of index -1.4 (but unattenuated since the opacity due to dust or trace elements below 13.6eV is relatively small). The continuum impinging the cloud is described by $F_\nu = F_s\nu^{-1.4}$. In number of photons this is $F_\nu/h\nu = F_s/h\nu^{-2.4}$. The constants F_s/h will cancel out when taking the ratio Π_{3d}/Π_{4s}.

The atomic data was taken from Osterbrock (1987) for H^0 and from Shine & Linsky (1975) for Ca$^+$ and Ca^{+*}. Tables 1, 2, 3 where we define $a'_\nu = a_\nu * 10^{18}$ and $\nu' = \nu/10^{16}$ show the repevant atomic data. The threshold ionizing frequency of H^0 is labelled ν_0.

We estimate the quotient Π_{3d}/Π_{4s} as follows:

$$\frac{\Pi_{3d}}{\Pi_{4s}} = \frac{n_{3d}}{n_{4s}} \frac{\int_{\nu_{3d}}^{\nu_0} \nu^{-2.4} a_\nu(Ca^{+*}) d\nu}{\int_{\nu_{4s}}^{\nu_0} \nu^{-2.4} a_\nu(Ca^{+}) d\nu} \quad (eq.1)$$

If we define $a'_\nu = a_\nu * 10^{18}$ and $\nu' = \nu/10^{16}$, we have

$$\frac{\Pi_{3d}}{\Pi_{4s}} = \frac{n_{3d}}{n_{4s}} \frac{\int_{\nu'_{3d}}^{\nu'_0} \nu'^{-2.4} a'_\nu(Ca^{+*}) d\nu'}{\int_{\nu'_{4s}}^{\nu'_0} \nu'^{-2.4} a'_\nu(Ca^{+}) d\nu'}$$

$$= \frac{n_{3d}}{n_{4s}} \frac{I_1}{I_2} \quad (eq.2)$$

The values of $a'_\nu(Ca^{+*})$ at ν'_0, ν'_{4s} and $a'_\nu(Ca^+)$ at ν'_0 and ν'_{4s} have been obtained by interpolation from (see Tables 2 and 3). Using the rule of the rectangle to approximate a given integral:

$$\int_{x_0}^{x_1} f(x)dx \sim (x_1 - x_0)f(x_0) + (x_2 - x_1)f(x_1) + ...$$

$$+(x_n - x_{n-1})f(x_{n-1})$$

Table 1. H^0 photoionization cross section

ν'	$a'_\nu(H^0)$	$\nu'^{-2.4}a'_\nu(H^0)$
0.3	6.4	115.1
0.4	2.5	22.54
0.6	1.15	3.919
0.8	0.6	1.025
1	0.3	0.3
1.2	0.2	0.1291
1.4	0.15	0.06689
1.6	0.1	0.03237
1.8	0.07	0.01708
2	0.05	0.009473
2.2	0.04	0.006029
2.4	0.03	0.00367
2.6	0.02	0.002019
2.8	0.015	0.001267
3	0.015	0.001074
3.2	0.01	0.0006133
3.4	0.01	0.0005302
3.6	0.01	0.0004622

(eq.2) reduces to

$$\frac{\Pi_{3d}}{\Pi_{4s}} \sim \frac{n_{3d}}{n_{4s}} \frac{10.06}{0.156} \quad (eq.3)$$

If we take into account that $\frac{n_{3d}}{n_{4s}} \sim 10^{-7}$ we obtain

$$\frac{\Pi_{3d}}{\Pi_{4s}} \sim 6 \times 10^{-6}$$

which means that the ionization of Ca^+ into Ca^{++} originates overwelmingly from the ground level 4s.

b) Ionization of Ca^{+*} by Lyα photons.

Lyα photons have energies slightly higher than the treshold energy of level 3d of Ca^{+*} and constitute undoudtedly an important source of ionization for this level. To compute the Lyα emissivity, we assume the low density regime whereby $\simeq \frac{2}{3}$ of recombinations of H^+ lead to the emission of a Lyα photon. Since Lyα is a resonnant line of large line scattering opacity, we consider that the density of Lyα photons within the Ca^+ region result from the production of Lyα either locally or from *deeper* regions. The justification for this is that resonnant line photons generated from layers nearer the slab'surface would be reflected outward as a result of the increasing fraction of H^o with depth (see Binette et al 1993b). Therefore the Lyα flux potentially available to ionize level 3d is a small fraction η of the total Lyα flux emitted by the cloud. This fraction is of order 0.2 corrresponding to the fraction of ionizing photons of H^0 *not yet* absorbed at the typical depth where the Ca^+ specie is abundant.

We first compute the $\Pi_{3d}^{Ly\alpha}/\Pi_{4s}$ ratio taking into account that resonnant scattering will increase the density of locally emitted line photons by a factor $\xi \sim 10^7$, the mean number of scatterings before escape. Such a high number of line scattering, however, characterizes only the locally produced Lyα photons. This accumulation (or slowing down) effect which we want to estimate is only effective within a zone of optical depth of order a few. Let's take $\tau_{scat} \sim 10 = \sigma_{scat} n(H^0)\,\delta X$ where δX is the geometrical depth and $n(H^0)$ the local density of H^0. Adopting $\sigma_{scat} \simeq 6 \times 10^{-14} cm^2$ (cf Appendix B of Binette et al 1993b), the column density of recombining H^+ we should consider in generating Lyα is within a thickness $N(H^+) \sim N(H^0) = n(H^0)\,\delta X = 10/6 \times 10^{-14} = 1.7 \times 10^{14} cm^{-2}$.

Taking these considerations into account, the problem reduces to estimating the quotient

Table 2. Ca^+ 4s photoionization cross section

$\lambda(\AA)$	ν'	$a'_\nu(Ca^+)$	$\nu'^{-2.4}a'_\nu(Ca^+)$
1044	0.2873 (ν'_{4s})	0.2036	4.063
1000	0.3	0.2097	3.772
950	0.3158	0.2145	3.412
	0.3288 (ν'_0)	0.2157	3.114
900	0.3333	0.2170	3.031
850	0.3529	0.2172	2.644
800	0.375	0.2149	2.262
750	0.4	0.2103	1.896
700	0.4286	0.2033	1.554
650	0.4615	0.1942	1.242
600	0.5	0.1830	0.966
550	0.5455	0.1700	0.7282
500	0.6	0.1554	0.5295
450	0.6667	0.1394	0.369
400	0.75	0.1225	0.2443
350	0.8571	0.1049	0.1518
300	1	0.0870	0.08697
250	1.2	0.0691	0.0440
200	1.5	0.0519	0.0199
150	2	0.0352	0.00668
100	3	0.0199	0.001417
50	6	0.0198	0.0002685

Table 3. Ca^{+*} 3d photoionization cross section

$\lambda(\AA)$	ν'	$a'_\nu(Ca^{+*})$	$\nu'^{-2.4}a'_\nu(Ca^{+*})$
1218	0.2462 (ν'_{3d})	6.148	177.70
1200	0.25	6.086	169.50
1150	0.2609	5.907	148.60
1100	0.2727	5.716	129.20
1050	0.2857	5.511	111.4
1044	0.2873 (ν'_{4s})	5.403	107.80
1000	0.3	5.295	95.22
950	0.3158	5.066	80.56
	0.3288 (ν'_0)	4.9465	71.39
900	0.3333	4.827	67.41
850	0.3529	4.576	55.72
800	0.375	4.315	45.43
750	0.4	4.044	36.46
700	0.4286	3.762	28.74
650	0.4615	3.47	22.19
600	0.5	3.168	16.72
550	0.5455	2.856	12.23
500	0.6	2.534	8.634
450	0.6667	2.202	5.827
400	0.75	1.862	3.714
350	0.8571	1.517	2.196
300	1	1.173	1.173
250	1.2	0.8424	0.5439
200	1.5	0.5401	0.2041
150	2	0.2865	0.05428
100	3	0.1051	0.007524
50	6	0.01471	0.0001995

$$\frac{\Pi_{3d}^{Ly\alpha}}{\Pi_{4s}} = \frac{n_{3d}}{n_{4s}} \frac{\frac{2}{3}\eta\xi a_{Ly\alpha}(Ca^{+*})N(H^{+})\int\limits_{\nu'_0}^{\infty}\nu'^{-2.4}a'_{\nu}(H^0)d\nu'}{\int\limits_{\nu'_{4s}}^{\nu'_0}\nu'^{-2.4}a'_{\nu}(Ca^{+})d\nu'}$$

$$= \frac{n_{3d}}{n_{4s}}\frac{2}{3}\eta\xi a_{Ly\alpha}(Ca^{+*})N(H^{+})\frac{I_3}{I_2} \quad (eq.4)$$

where $a_{Ly\alpha}$(Ca^{+*}) is the photoionizatiom cross section of Ca^{+*} at the Lyα energy ($\simeq 6\times10^{-18}cm^2$). Taking again $n_{3d}/n_{4s}\sim10^{-7}$, we obtain

$$\frac{\Pi_{3d}^{Ly\alpha}}{\Pi_{4s}} \sim 1.36\times10^{-4}\frac{I_3}{I_2} \quad (eq.5)$$

Using again the rule of the rectangle we obtain

$$\frac{\Pi_{3d}^{Ly\alpha}}{\Pi_{4s}} \sim 1.5\times10^{-2}.$$

The effect of slowing down of resonnant line photons is interesting but appears insufficient as it envolves too small a fraction of the Lyα photons generated within the nebula. Let's now estimate the importance of all the Lyα photons generated within the deeper zones which, after having scattered far enough in frequency to escape, must still cross the Ca^{+} zone (without appreciable scattering in that zone). The effect on the photoionization of level 3d is given in this case by

$$\frac{\Pi_{3d}^{Ly\alpha}}{\Pi_{4s}} = \frac{n_{3d}}{n_{4s}} \frac{\frac{2}{3}\eta a'_{Ly\alpha}(Ca^{+*})\int\limits_{\nu'_0}^{\infty}\nu'^{-2.4}d\nu'}{\int\limits_{\nu'_{4s}}^{\nu'_0}\nu'^{-2.4}a'_{\nu}(Ca^{+})d\nu'} \quad (eq.6)$$

$$= \frac{n_{3d}}{n_{4s}}\frac{2}{3}\eta a'_{Ly\alpha}(Ca^{+*})\frac{I_4}{I_2} \quad (eq.7)$$

(Note that a' is used here for Ca^{+*}). Using the rule of the rectangle we obtain

$$\frac{\Pi_{3d}^{Ly\alpha}}{\Pi_{4s}} \sim 2.43\times10^{-6}$$

In summary, Lyα emission and/or trapping are insufficient to ionize Ca^{+}. As in the case of soft continuum photons, this is basically the result of the extremely small population characterizing the excited level 3d.

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